

N63-14149

Session on Solar Energy Conversion

RADIATION-RESISTANT SOLAR CELLS

A Panel Discussion

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OPENING COMMENTS

CHERRY, *Chairman*

In 1959 a program to investigate improved silicon solar cells was initiated at the U. S. Army Signal Research and Development Laboratory. The study, under the technical guidance of Mr. Joseph Mandelkorn, was directed toward the construction of solar cells under highly controlled conditions and with phosphorous diffusion at temperatures much reduced from conventional methods. By early 1960, 10% efficient cells were being constructed and subjected to routine evaluation and analysis. While these devices did display improved diode characteristics, in general the overall properties of the N-P solar cells were quite similar to the commercial P-N cell.

Testing of samples of the phosphorous diffused cells in May 1960 for radiation damage studies on a comparative basis with commercial cells revealed a significant difference between the two varieties. This was not a predicted result, but certainly a very significant one in view of the known radiation hazards in space surrounding the earth. This panel will discuss the radiation damage to and radiation resistance of solar cells.

MANDELKORN

Our latest work covers the development of high resistivity silicon solar cells and the bombardment of these cells, with 1.2 mev protons. We had noted from the work of others that under bombardment by low energy protons there is a significant difference between the radiation behavior of these cells when compared to bombardment by higher energy protons. We bombarded with the low energy protons and, as we discussed at last year's conference, it appears that the high resistivity N-P cell did have considerably higher radiation resistance than our 1-ohm-cm² high blue N-P cell. In the past year, bombardment of these high resistivity cells was carried out at both RCA and Bell Telephone Laboratories. In addition, we recently bombarded these cells at our Laboratories with neutrons. I would like to mention the general conclusions. First, we find that efficiencies of 10 to 12% are readily achievable using resistivities of 10 to 20 ohm-cm². It is most interesting that these efficiencies are achievable using the identical fabrication process as was used to obtain high blue, 1 ohm-cm² cells. The high resistivity cells have somewhat

better blue collection; they have considerably higher minority carrier diffusion lengths in the base region and consequently very high red collection and they have significantly better junction characteristics. Under 100 mw/cm² sunlight intensity, the short circuit currents, of cells made from high resistivity material in the range of 10 to 80 ohm-cm², are approximately 2 to 3 mils higher than that of cells made of typical 1 ohm-cm² material. The open circuit voltages of these cells varied with the resistivity of the material.

For the 1 ohm-cm² cell, the open circuit voltage is 0.61 volts. It is well known that .61 is a pretty high value of open circuit voltage at 25°c. On the 10 ohm-cm² we have been able to obtain .55 volts; on the 20 ohm-cm² .525 volts; on the 50 ohm-cm² .490 volts and on the 80 ohm-cm² .460 volts. We have been able to obtain efficiencies of 8.5 to 9% on 80 ohm-cm² material. These are sunlight measurements at high intensity using Krylon as a coating. Under bombardment, there is considerably slower degradation of the diffusion length of the minority carriers in the base region of cells made from 10 ohm-cm² P type material than cells made from 1 ohm-cm² P type material.

Degradation has been measured under 1 mev electron bombardment at BTL and has been found to be reduced three-fold. This is also true for neutron bombardment. This is diffusion length degradation which is to be differentiated between some of the other types of measurements. After heavy bombardment of equal fluxes of neutrons and electrons, the 10 ohm-cm² cell maintains an efficiency of approximately 1% higher than that of the 1 ohm-cm² cell. Interestingly enough, there is no significant improvement in terms of lower base minority carrier diffusion length degradation under bombardment in going from 10 ohm-cm² cells to 50 ohm-cm² cells.

The very high resistivity material did not improve the red collection of these cells made by the standard process. Apparently we were able to preserve just so much lifetime and therefore it does not make any difference what higher resistivity material is used.

Finally, we have found consistent results between laboratories, although sample quantities of cells have been small. It is believed that N-P cells made from 10 ohm-cm² material will have at least double the radiation resistance of N-P cells made from 1 ohm-cm² material.

SMITS

The effort at the Bell Telephone Laboratory has been concentrated on evaluating solar cells. It has been recognized that the evaluation of cells as to their performance under actual outer space Sun conditions played a major role. Some of the arguments which are going on are associated with the present difficulty in comparing results between different laboratories. This becomes particularly pronounced if you go into some of the more exotic cells, like the gallium arsenide cells, or cells that have a vastly more different spectral response characteristic such as heavily pre-bombarded silicon cells. At the present time I feel that the only readily available solar cell type that is more radiation resistant than the commonly used P-N cell is the 1 ohm-cm² N-P cell. As Mr. Mandelkorn indicated previously, there are apparent improvements if you go to higher resistivity N-P silicon cells. The quoted factor of two to threefold improvement can only be taken as proof of feasibility and one can expect that it actually can be realized.

I feel also that at the present time the other solar cells, like gallium arsenide, is still an open question. There is a claim, that it may be superior radiation wise. In particular, I feel we should also include temperature considerations in such evaluations. There are also scattered reports that solar cells made from different materials, such as oxygen free material might be better. I personally feel that we do not know at all how the defect introduction works. There is good chance that by adding impurities or deleting mutual impurities, we may effect radiation sensitivity. There has been one experiment at BTL, using pile neutrons which indicates that neutrons and protons produce equal damage, rather than a ratio of 100 or 1000 to 1 as expected by theory. This is unusual and we don't understand it yet. Similarly we still have unresolved questions as to the energy dependences of the proton damage. These are areas in which I see future work being done both at BTL and STL and possibly also by other organizations.

RAPPAPORT

Our program at RCA has been threefold in nature:

- (1) The accumulation of engineering type data
- (2) An investigation of the threshold
- (3) The study of the materials parameters and how they influence the radiation resistance of solar cells.

This work is being supported by NASA and was supported by the Signal Corps. As for the engineering data Figure 1 is a summary of the ϕ_c 's, the critical flux, or that flux which produces a 25% deterioration in the power output of the solar cell. I accept Smits remark that this is not the best parameter to report; however, we feel that it is one of the more significant parameters. Obviously, looking at the whole curve is much superior to this.

For proton irradiation of silicon at 19 mev, you will note a threefold improvement for the N/P cell over the P-N. At 8 mev, this factor is 2.4. We are disconcerted that this energy dependence here is somewhat in the reverse order that we had anticipated. We had thought that ϕ_c would be larger for the higher energy. However, this is not a big factor and may be explained someday. The most significant fact is that there is a definite improvement with the N-P cell for proton irradiation which also has been corroborated in satellite experiments.

The next column down shows the results for electrons at .8 mev. Here, we have considerable spread in the data. The results show a magnitude increase in the critical flux for the N-P cell. This also has been corroborated by others. The gallium arsenide cell at 19 mev shows a spread between 2 and 8×10^{12} for the critical flux. Dr. Smits pointed out the possibility of some error here because of the fact that these measurements were made under tungsten light. We have made many measurements on silicon cells, comparing both tungsten and sunlight. We belong to those that say that the tungsten light source is the worst light source to use to make these measurements. On the other hand it is the most convenient. Our results indicate that tungsten light will show the cells to be poorer by a factor of about 20 to 50%. In other words, for the silicon cells, these results on the chart are conservative by 20 to 50%. However, they are still a magnitude poorer than the gallium arsenide cell based on this preliminary data.

The threshold work gives us a very sensitive method for determining the radiation damage characteristics of P-N junctions. We do this with electrons going from very low energy electrons from 100 Kev to 800 Kev. This gives us a good bit of information on the behavior of P-N junctions. It does not quite tell us what it will do as solar cells but it gives us leads.

We agree that the higher you go in material resistivity the more radiation resistant the cells appear to be. We also have

SUMMARY OF ϕ_c 's FOR VARIOUS SOLAR CELLS

Material	Radiation	No. of Cells	ϕ_c/cm^2		
			P/N	N/P	
Silicon	protons	19 mev	20	$1.9 \pm 1.7 \times 10^{10}$	$5.5 \pm 0.2 \times 10^{10}$
		8 mev	14	$3.5 \pm 2 \times 10^{10}$	$8.4 \pm 1 \times 10^{10}$
Silicon	electrons 0.8 mev	100	$10^3 - 10^4$	$10^5 - 10^6$	
GaAs	protons 19 mev	10	$2 - 8 \times 10^2$		

Figure 1.

found that a lower processing temperature, of 875°C, rather than 975°C, is advantageous for the N-P cell. It gives us more consistency in processing, and in all cases the cells are more radiation resistant. We can theorize on some of the possibilities here but we don't really understand the physics of what is going on. We have seen as much as a tenfold improvement where the only variation has been this 100°C difference in processing. We have also conducted some studies of the material parameters of the base materials, the dopants, the resistivity. In general these are not as significant as the oxygen concentration. We recently re-analyzed some of our data and found that there does seem to be a significant improvement in N-P solar cells where we used floating zone material and where the processing excluded the introduction of oxygen.

For example, if you use P_2O_5 you apparently introduce enough oxygen into the processing so that there is no difference between quartz crucible material and floating zone material. On the other hand, if you start out with floating zone material (which has perhaps a thousand times lower oxygen concentration), and if you process with either pure phosphorous or indium phosphide, you can obtain a two or three-fold improvement in ϕ_c as measured by electron damage.

DOWNING

Most of the work we have been doing has already been summarized but I might emphasize that we are spending considerable time to determine the dependence of the damage rate on the proton energy. We have conducted experiments ranging from 2 mev to 740 mev and have also generated a classical model to which we can apply the experimental data.

The energy dependence of solar cell damage under electron bombardment follows very closely the relativistic Rutherford scattering equations. This dependence initiates at electron energies of 150 kev and rises rapidly to an approximately energy independent level for energies greater than 1 Mev due to the relativistic nature of the electrons. Apparent differences in the displacement cross section for P on N and N on P cells are observed in the region of 150 kev to 600 kev wherein N on P cells are relatively unaffected. This effect vanishes at higher electron energies and both types of cells follow the Rutherford scattering relationships. The energy dependence of cell damage under proton bombardment, however, is a complicated function of energy involving both Rutherford scattering and inelastic nuclear collision kinetics. Though the processes and equations concerning these effects are beyond the scope of this paper, they can be summarized by a $1/E \log T_m/E_d$ Rutherford scattering dependence for energies between a few Mev and about 100 Mev. Above about 100 Mev, the proton damage is dominated by inelastic nuclear interactions, "spallation." Consequently, the proton damage is relatively insensitive to the proton energy above about 100 Mev. The energy dependence of damage for both electrons and protons has been found experimentally to agree with the theoretical relationships within the accuracies and assumptions involved.

Variations in behavior in different types of cells when subjected to identical radiation environments have been observed in all cases. Under electron bombardment at energies near 1 Mev and above, N on P cells are found to be a factor of 20 more radiation resistant than P on N cells. Under proton bombardment, however, the N on P cells are only a factor of 3 to

5 better than standard P on N cells for all proton energies. Experiments using solar cells constructed of float zone refined silicon have provided some interesting results. Proton experiments conducted at 20 Mev indicate that P on N cells constructed of float zone refined silicon are of the order of a factor of 5 more resistant than standard P on N cells and similar in response to N on P cells. Under electron bombardment, however, this relationship does not occur. Further studies of these phenomena are continuing.

The previously mentioned differences in cell behavior, i.e., P on N versus N on P under electrons and protons and the apparent differences in behavior of oxygen free silicon under electrons and protons, suggest that the radiation sensitivity is controlled by complicated interactions between the radiation produced defects and imperfections such as dopants, trace impurities, dislocations, etc. Experiments are being conducted in which radiation induced diffusion length degradation is examined as a function of various imperfections of the type mentioned above. Results from these studies should, in addition, yield information pertinent to the observation that damage rate variations in P on N devices are almost an order of magnitude greater than that observed in N on P devices. It is anticipated that the results of this program will help to identify the important interactions and, hence, allow the construction of more radiation resistant solar cells through appropriate control of either material or processing techniques.

ROSS

The attempts to reduce the effects of hard radiation upon solar energy converters have been largely confined to two areas. One, to reduce the actual effect on the diffusion length of the minority carriers and the other one, which has not been tried as much, is to make the process of conversion less dependent upon the diffusion length. We have made a number of different solar cell structures N-P, P-N, shallow, and deep diffused, and oxygen free. Our present effort is to depart quite severely from the previous structures and to go to a drift collected solar cell, in which the collection of the minority carriers does not depend upon diffusion and is therefore independent of the lifetime of the minority carrier which most easily falls prey to hard radiation induced recombination centers. Our approach is as follows: We take a substrate of very low resistivity silicon, quite heavily doped, let's say with a donor impurity. This substrate is subjected to an epitaxial growth to produce a layer of about 10 to 50 microns thickness of very high resistivity and of the same conductivity type as the substrate. Subsequent to this, we diffuse both the impurity that is contained in the substrate on the bulk side and an impurity that is placed on the surface from the surface direction. In this way, we obtain a junction in the epitaxial layer which should have some of the happy properties of Mr. Mandelkorn's cells in that it essentially will be a high resistivity type junction. It should also allow you to take advantage of the electric field which is created in the bulk and which will be something on the order of 500 volts cm^{-1} . This electric field will put a definite urging upon the minority carriers that are released in the bulk from the red radiation. We already have such a field in the front surface diffusion of which present cells are capable of taking advantage. The amount of resistance to radiation will hopefully be increased by a factor of 5 to 10. Another possible advantage from this is that you will

get a solar cell with a higher equilibrium barrier voltage which should operate at a higher operating voltage and have a higher open circuit voltage. The actual results of this investigation are not as yet available. It is difficult to grow an extremely high resistivity epitaxial layer upon an extremely low resistivity substrate.

WOLF

Our approach is to enhance the short wavelength response as it is not dependent on long diffusion lengths or minority carrier lifetimes which degrade under the influence of radiation. This can be done by making the junction depths as shallow as possible. We have done this as far as one can in P-N and N-P cells. Recently, we began studying the effects of drift fields in the base. It is too early to report on the results. Beyond this we have looked into the applicability of other materials which would have higher absorption coefficients and therefore not need the long diffusion lengths in order to collect carriers generated by protons which penetrate deeper into the material.

Gallium arsenide seemed to be, for quite sometime, a material which would be ideally suited for this purpose since it is a direct semi-conductor with a sharp absorption edge. The more recent radiation results about which we heard today does not give us quite as much of a difference as one might expect. There is another semi-conductor namely Cadmium Sulphide which has been shown to be very radiation resistant recently.

This is to be expected since the mechanism in Cadmium Sulphide is a photoemissive process on a semiconductor metal interface, at least to a large extent.

HUNRATH

Since Mr. Mandelkorn has presented the work being done on radiation resistant solar cells at our laboratory, I will discuss the view point of the solar power supply system design engineer and some of the problems he is confronted with. We have heard that as a result of the Explorer XII radiation experiments Van Allen's concept of two distinct radiation belts is no longer valid. There is one huge belt extending from 300 to 40,000 miles. What we don't know is just what is the flux and energy level of the electrons and protons at various altitudes in the radiation belt. Satellites have operated fairly well at the lower altitudes but some of the future satellites will be at much higher orbits.

What protection should we provide for these cells (if it is at all practical) and what type of cell should we select for a particular power supply? We have been hearing about the advantages of the "blue" P-N, versus the N-P and we have also heard today of the superiority of the gallium arsenide cell over the N-P. The solar power supply design engineer needs guidance in these problem areas.

GENERAL DISCUSSION

MANDELKORN

It was mentioned here that there was a plateau in the proton energy damage versus energy of protons above 100 mev. It was always our feeling there was an irregularity in the proton damage versus proton energy characteristics in the range of approximately 2 to 5 mev. I recently heard, Dr. Smits, that your people have collected some information on this.

SMITS

I try to stay away from this sticky point; however being forced into it let me describe the experiments that were conducted by Mr. W. Grossensweiger of Bell Telephone Laboratories. We performed radiation damage studies under 5 mev in a Van der Graf at the Naval Research Laboratory which could be regulated down to 2 mev; at 18 mev in the cyclotron at Princeton University, where the beam energy was cut down by absorbers to 6 mev. The third machine we used was the cyclotron of the Harvard University where the initial energy was about 140 to 150 mev; again by absorbers it was reduced down to 24 mev. In between was this experiment run last week at McGill University which is a 100 mev machine. Again we used the absorber technique to cut the energy down to 21 mev.

Then there is the lonely point at 450 mev carried out by STL at the Chicago cyclotron. We find the $1/e$ slope from 450 mev down to approximately 40 mev. We find a plateau between 40 and 5 mev and again a $1/e$ slope below 5 mev. It is somewhat peculiar that the break from the plateau back into the $1/e$ slope occurs just at the break between two machines. This will have to be further explored. However at the present time we can't see a thing wrong with the experiments; particularly, in the experiment at the Princeton cyclotron, reducing the energy shows a plateau between 6 and 20 mev. The Harvard and McGill experiments both show a plateau below 40 mev.

MANDELKORN

I would like to ask for comments on whether there has been any further observation of room temperature annealing in the N-P cell.

SMITS

Very definitely yes. We have performed very careful experiments to establish this and there is annealing in the order of 10 to 20%.

MANDELKORN

Is this under electron bombardment or only under proton bombardment?

SMITS

It has been predominately observed under proton bombardment. I am not aware of much work under electron bombardment.

CHERRY

At what energies did you observe it?

SMITS

The careful experiments were done both at the 20 mev level and the 140 mev level.

CHERRY

Nothing from 400 mev up?

SMITS

No, we have not yet been using these energies. The 450 mev experiment was only a preliminary one.

CHERRY

Downing, you have done quite a bit of high energy proton bombardment. Have you noticed anything of this nature?

DOWNING

In the experiments, started a few years ago, conducted at 740 mev, 450 mev and 400 mev using mostly P-N cells, we observed no annealing. At temperatures up to approximately 200°C we could force no recovery. At that time, we more or less assumed that the work done by Benski and Agusti was sufficient. It was after that when we irradiated our first N-P cells in Chicago, that the question of annealing on N-P came up. We went back and looked at some of these cells and we did measure, qualitatively, annealing of the order of 10 to 20%. We are now starting to look at the P-N and N-P cells irradiated at McGill last week, very critically, for just this very point.

CHERRY

Rappaport, in your electron and proton work have you made any observations concerning annealing at any temperature?

RAPPAPORT

We have seen some annealing effects in our runs but actually we haven't investigated this quantitatively. A number of years ago we had observed annealing effects on electron bombarded junctions and looked carefully at it. We saw annealing effects at 1 mev in the order of 10 to 20%. I think a very worthwhile study is to look at either the annealing or introduction rate as a function of temperature, especially when one talks about the higher operating temperatures of solar cells.

SMITS

I would like to add one curiosity to the curious observations in the case of annealing. We had observed at one point, what one might call negative annealing. If you take a pre-bombarded cell you find that the radiation damage gets worse during the soldering operation. It only serves to illustrate how little we know about the introduction of these defects.

AUDIENCE

Would you call that negative annealing or just plain annealing?

SMITS

No. It is negative annealing as the cell response goes down. Annealing means an increase in cell response. The damage increases rather than decreases under this heat treatment.

MANDELKORN

I would like to get some information from Dr. Smits on the time constant. I feel that this is the actual problem. It must have a very rapid time constant and therefore has gone undetected. Now, would you say this is so?

SMITS

A cell which was measured on April 10, 1962 had a 11.5 microns diffusion length. This was measured while in the proton beam. The next day it was 12.3; the following day 12.7; two weeks later 13.9 and yesterday 14.1 microns. This shows that the time constant may be expressed in days to weeks.

ROSS

This question is directed to Mr. Mandelkorn and possibly Dr. Smits. Do you have any explanation for the mechanism of reduced radiation damage in a high resistivity solar cell?

MANDELKORN

The only thing I can say on this is it really would depend on where the level of the recombination centers are located.

There has been considerable measurements made by people of the recombination center levels. Offhand, the measurements made do not correlate with the information we have. In fact, by means of the data we have accumulated you can speculate where the recombination center level might be located but I think it needs much further work. This is the only explanation I can think of at this time.

SMITS

The only answer I can give to that question is no. It is however, plausible, because it generally is the case that a given recombination center reduces the lifetime less strongly in high resistivity material than in low resistivity material. Reference Shockley's recombination theory.

ROSS

In some studies that we have carried out about six years ago we determined that the recombination levels that are introduced by quenching are on the order of 1/10 of an electron volt away from the band edge regardless of the band edge. This was done by a thermal activation energy type study. I would like to ask if something of this sort has been done with irradiated materials and if you could confirm or deny this value of the recombination center level.

MANDELKORN

I think some reports contain the information that the level was about .27 electron volts away from the band edge.

ROSS

I would like to make a further comment, it is interesting that one can produce an equivalent situation to a highly irradiated cell by quenching. In other words by taking the cell from a high temperature and quickly reducing the temperature. I wonder if any one has attempted to establish whether pre-irradiated cells behave similarly to hard quenched cells.

SMITS and MANDELKORN

No.

SMITS

I would like to make a comment, picking up what Mr. George Hunrath indicated before. We device people may be fooling the systems people here a little bit if we talk about an increase of a factor of 10 in radiation sensitivity. You should realize that the slope of power output versus flux shows only 20% per decade. Thus, if the systems people can manage to lower the temperature of the cells, such that, its power output increases by 20% they do the same thing as increasing the radiation resistance by a factor of 10.

I would like to remind you to keep the overall requirements in mind in the design of such systems.

CHERRY

I might say that there is a bit of good news. The electron densities observed by Van Allen in some of the experiments seem to reduce by three orders of magnitude, the original estimate of electrons around the 1 mev level, are down to something of the order of 10^8 cm²/sec. Does anyone on the panel have a comment here on the life of a solar cell at 1 mev electrons with no cover glass.

RAPPAPORT

We have a comparison which is based on the short circuit current decay for N-P and P-N cells. Based on the early Van Allen data, in ten days a P-N cell is down to about 70% of its original output whereas an N-P cell in 9 months is down to that level. This is with no shielding.

DOWNING

If you use 10^8 cm²/sec, this is approximately 3×10^{15} cm²/year. I think that we are all in pretty much agreement that commercially available P-N can be expected to be down by 25% at about 1×10^{13} . On the other hand, an N-P cell exhibits a radiation resistance of about a factor of 20 greater under these energy electrons, so you are talking about 2×10^{14} for about 25% damage, which is essentially 1/10 of a year, so that even at 10^8 , an unshielded cell is going to suffer measurable degradation in a year.

RAPPAPORT

I think the real problem of course is the protons because you can shield against electrons. In this meeting at NASA at the end of February there were some very alarming numbers given which indicated something like 10^6 protons per cm²/sec at a 2000 mile altitude. That was Lockheed data. That is a fantastic flux, it depends of course on the energy. I am very anxious to see more results on measurements with different thicknesses of glass or quartz films so that the energy of this type of radiation can be determined.

CHERRY

I just happen to have some information on Explorer XII which had an extremely elliptical orbit. It had a perigee of about 182 miles and an apogee of about 48,000 miles.

On this experiment Longernecker reported that they ran unshielded cells (that is with no cover glass at all) solar cells with 3 mils of glass; 20 mils of glass and 60 mils of glass. Explorer XII continued to put out information for 112 days. When passing through the high proton fields at about 20,000 miles, the unshielded cells degraded in two passes by over 50%. The 3 mils cover glass cells suffered about a 6% degradation in about 120 days so that the glass was able to stop a good deal of the damage.

The 20 and 60 mil cover glass had no detectable degradation at all. This emphasizes rather strongly the importance of cover glasses. Now these were P-N cells. "Relay," which is due to go up at the end of this year will give us more information of this type.

HUNRATH

Doesn't that experiment reflect the integrated damage over the entire belt rather than the damage that would occur at some specific altitude.

CHERRY

Yes, but the damage did occur at this specific altitude. They could see when it passed through this major field where the degradation occurred, very abruptly, at these two passes on the inbound flight.

HUNRATH

Have they been able to determine just what the flux and the particle energy is at that altitude from their detectors on board?

CHERRY

I don't have that information with me. I think they have calculated what it is.

MANDELKORN

I have a vague recollection of the fact that this damage came about from low energy protons rather than electrons. I believe they found something at energies in the order of 2 mev or so. There was something like 10^7 protons and this is one of the comments which is related to the fact that I was very interested in the plateau in the low proton energy segment of the N-P damage curve. In general, you can expect that the high energy protons will be slowed down in the cover glasses and their energies reduced so it is of interest to note the behavior over the entire proton energy spectrum.

DOWNING

As was mentioned at a meeting in Philadelphia, at the General Electric Company, about a month ago, we have a contract, through the Air Force, to fly some piggyback experiments. Now these experiments should be up fairly soon and the data should be available by the first of the year.

We will be flying experiments covering shield thicknesses, N-P versus P-N and some, in a later stage, with gallium arsenide cells on it. This should give us some information that will be very helpful concerning the space problem directly.

CHERRY

I might just add in conjunction with your statement that the NASA will have an experiment using P-N and N-P and gallium arsenide cells with bare cells as well as cover glasses of various thicknesses. This is going to be a very interesting experiment, I am sure. It is going to have an orbit that will put it into these major areas.

SMITS

The Telstar experiment covers the test of solar cell response only on N-P under three different shield thicknesses. In addition to that it will use specially designed transistors which have a radiation sensitivity of a factor 10 higher than you would expect from solar cells. Yet it is the same type of material that the N-P solar cells are made from. Any information obtained, immediately applies to the N-P solar cells. The reason for using such a transistor is to avoid the difficulty you always encounter in a spinning satellite where the test solar cells have a time varying illumination.

Telstar will use simultaneous measurements of pre-bombarded cells and unbombarded cells so that you can use the pre-bombarded cells as an indication of the attitude. Unless you do some complicated things which may cause difficulties

you cannot get much information from the solar cells. Another alternative is to use a very high repetition rate in the readout and actually get normal incidence information which requires lots of telemetry bandwidth. Such a transistor is independent of this and all you measure is the current gain and you get radiation damage information.

ROSS

There were some solar cell experiments by RCA. I think on the Tiros and by John Hopkins on some of the Transit flights. Now Johns Hopkins has not been below 555 miles maximum altitude. However, in this experiment they did find definite degradation whereas Mr. Winkler of RCA indicates that they had flown bare cells at a circular orbital altitude of approximately 380 miles and found absolutely no degradation of solar cells. This type of information is interesting since more and more low altitude circular flights are being planned.

DOWNING

Concerning some of these lower altitude shots where some people saw degradation and thought it shouldn't be and vice-versa. We have conducted at STL some independent experiments on an associated problem, namely combined ultra high vacuum and ultra violet in vacuums at 10^{-9} and 10^{-10} with ultra-violet light exposures of 60 to 120 days. We have found catastrophic changes in the glue which is used to bond cover glasses on cells. The use of a UV filter has a large effect on it. The effect that we are seeing, is much larger than I think we had anticipated.

I think that some of the degradation, for instance in the track satellite at 575 miles, may be attributed to this. It does not necessarily mean that it was radiation at that altitude.

AUDIENCE (Mr. J. Leisenring, Spectrolab)

Is the data taken on the radiation experiments and documented as a function of the cell temperature at the time it is irradiated?

SMITS

I think that all the experiments we discussed here were done at room temperature. I happened to know that someone here in the audience did some experiments as a function of the radiation temperature.

AUDIENCE (Mr. J. Peden, General Electric Co.)

We did do some experiments recording the cell temperature during the irradiation at $+150^{\circ}\text{F}$, $+85^{\circ}\text{F}$ and -150°F . We did not take any diffusion length measurements. We just measured the degradation as a function of the dose. We got the results we anticipated.

The damage is a little increased with cell temperature. We measured the cells also at 6 different temperatures, ranging from -200 to $+200^{\circ}\text{F}$. If one measures all the cells at 85° , you would get increased damage for the cell held at the higher temperature during irradiation. The temperature dependence of the cells changes as a function of the radiation too.

RAPPAPORT

I want to say that we do consider temperature, and all our runs are made at 15°C . The cells are on a water cooled copper block.

SMITS

Some experiments were performed by Dr. Brown and others at BTL. The general behavior is that if you bombard at a lower temperature, and measure at this low temperature without ever letting the cell come up in temperature, you observe a higher rate of damage introduction. If you bombard at a low temperature and measure at room temperature, the damage rate introduction is lower than if you bombard at room temperature. This sounds funny, but it makes sense because the particle knocks off atoms. If you have it at a lower temperature, there is not enough thermal agitation to help you displace atoms. However, smaller displacements are frozen in because they don't recombine. Then if you go to room temperature, the smaller displacements disappear and you are left with an overall lower introduction rate. Similarly if you bombard at higher temperature, you have thermal motion to help you displace atoms. Thus you get the higher introduction rate.

ROSS

I wanted to ask a question of Mr. Peden of the General Electric Company, as to whether this study of irradiation at higher temperatures took into account the annealing effects that might have been present.

PEDEN

We were naturally worried about the annealing. We looked at this and did not find any annealing at any of the temperatures. Our work was on red P-N cells. The highest temperature was $+150^{\circ}\text{F}$.

AUDIENCE (Mr. Flicker, RCA)

We also did some measurements, mostly at room temperature, as Mr. Paul Rappaport indicated, and some at freon and liquid nitrogen temperatures as well. We are looking at the electron voltaic effect and at energies of 150 and 300 kev. We get a rather peculiar effect in that the electron voltaic effect indicates a slightly higher rate of damage as we cool to freon and a slightly lower rate of damage as we cool to liquid nitrogen. We are fairly certain of this. I think what is happening is that there is some form of trapping, that is, the probability of occupancy of a recombination center becomes greater as you cool a sample so that the recombination centers are more effective as you cool down to freon. If you cool down to liquid nitrogen the lattice is stiffening and it is harder to produce a defect.

AUDIENCE (Dr. Baretta, NRL)

This question is for Dr. Ross. Did you say this degradation of the cells occurred in areas where it was not expected?

ROSS

I did not say it occurred in a region where it was not expected. They found it at 550 to 575 miles.

AUDIENCE (Dr. Baretta, NRL)

Possibly the degradation may have been of the glue itself. I was wondering if this possibility is true. Has the possibility of conducting an experiment with a highly pre-irradiated cell and one that is not, been considered?

DOWNING

We are flying just this type of experiment on this project that I mentioned.

AUDIENCE (Mr. Fred Gordon, USASRDL)

Did you notice any time constant in the annealing after proton bombardment, Dr. Smits?

SMITS

I don't have this information available at the present time because the observation of the annealing effects is tied to fairly recent improvements in the technology, where we measure the diffusion length under the proton beam using the ionization of the protons themselves; thus getting very good information at time zero. This only has been going on fairly recently and data have not been analyzed with that in mind. However, I would be surprised if there is a very significant energy dependence. One thing we feel has been established beyond doubt is that the ratio in radiation sensitivity between the various types of solar cells is energy independent for protons. It would be surprising if one would get such additional effects which show a strong energy dependence. In the first place the effect is small anyhow and hard to pin down.

CHERRY

I would like to ask about the merits of measuring, in radiation degradation, the short circuit current as a criteria versus the power output as a criteria. I noticed that some people have used the ratio of the short circuit current, others have used changes in maximum power. I would like to ask the panel which would be a better way to get information regarding degradation.

MANDELKORN

I think this has been a very burning issue and it is primarily one of the reasons why we have so many conflicting reports about which cells are more radiation resistant and what the radiation resistance of cells is in general. I think the pattern has been set by the Bell Telephone Laboratories, in that the measurement of efficiency degradation is not the primary factor that we are after. It is the measurement of power degradation, in which we are interested. This is isolated from the design factors and the elements of the cell which are not radiation dependent. To illustrate this point, you can make two cells which have the very same lifetime in the base, but the cells may differ by two percent in efficiency, simply by the design factors such as the sheet resistance, the depth of the junction, the contact resistance, and the open circuit voltage behavior of the cell.

Typically the difference in efficiencies after heavy bombardment may be in the order of 1 percent or less, yet the cells differ by 3 times in radiation resistance. Now if we take a number of cells, some of them have better design characteristics, others have poorer design characteristics, the design characteristics will completely obscure the difference in the basic factor which is the degradation of the lifetime in the base region. I therefore feel very strongly, and I hope we can get some confirmation of this, that the measurement of efficiency or power output is not the thing. I feel definitely that the measurement of the diffusion length degradation as car-

ried out by BTL is really the very important parameter we are after.

WOLF

The basic material property which is changing under the influence of irradiation is the minority carrier lifetime which gives rise to the diffusion lengths. If you want to study materials and find out which materials are more or less radiation damage susceptible, then the measurements of diffusion lengths is definitely the right parameter. If you want to include device design parameters beyond the material properties then the accumulation of the material properties and the device design parameters is expressed in the short circuit current, if you measure under the same type of light source.

As for the power output of the cell as a function of radiation damage it actually is a secondary effect, since the power output is a product of current and voltage and the current changes at the maximum power point pretty much in proportion to the short circuit current. We cloud the picture a bit if we use power output. The diffusion lengths, minority carrier lifetime or short circuit current are the parameters which will teach us most about radiation damage.

SMITS

I feel that I have to differ. The ultimate requirements we would like to know and the application engineer wants to know is what the device will do in terms of absolute power output. He has a need for so many watts after so much exposure in the radiation belt. What he wants to know is how many watts can I get per solar cell after that exposure.

The way we supply this information is the second question. The actual power involves the whole string of parameters which go into the cell design. Only one of them is the radiation sensitivity of the minority carrier lifetime. Thus we feel very strongly that you have to evaluate the product as to its power output by a statistical method, because there are so many parameters involved. You get a variation and, after all, a satellite uses thousands of solar cells; thus its output is the statistical average of all the cells. If I want to correlate the damage between protons of different energies and electrons, I do not have to do that, it would be far too much work. I can concentrate on just studying the radiation damage parameter only. That is why we choose to study the minority carrier diffusion length because it has a clean theoretical relation with the particle flux.

All you need is a pre-bombardment measurement and an after bombardment measurement and you know the whole history. Anything in between is already redundant. Thus, the approach is to correlate, by diffusion length degradation, relative damage rates between radiations. Thus you can then derive equivalent radiation belt diffusion length degradation rate in terms of so much degradation per unit time. Under any convenient radiation you then can correlate this with actual power performance.

DOWNING

We are measuring both. The engineers and the systems designers need the short circuit current, IV and spectral response. As Dr. F. Smits pointed out the diffusion length may

be more interesting. On the subject of $\frac{I}{IO}$ plots, we started

out a few years ago using this. We did that as a matter of convenience because, then, the only cells that were available,

were P-N and they were all pretty much alike. Obviously ^IIO is meaningless unless the short circuit currents of the cells you are talking about are almost identical initially. Since this condition is no longer true (we have a large variety of different types of cells having somewhat different characteristics) to

use ^IIO without understanding what the initial conditions are is meaningless. For that reason we are now plotting short circuit current densities.

ROSS

I vote for the short circuit current for the simple reason that this is easy to measure. It is not affected to anywhere near the degree that the maximum power point is by temperature. I am chiefly talking about flight experiments and not surface experiments. The only way that you can measure some of these other parameters is to either put up a lot of apparatus or an analogous device not a solar cell. I feel that the short circuit current is the parameter which can most easily be measured by anybody with simple instrumentation with a fair degree of leeway on temperatures and other such things which are not easily measured on a satellite with accuracy.

AUDIENCE (Mr. Lamorte, RCA)

If one measures the current alone and/or the open circuit voltage this may not be any indication of the power output for you are not determining the change which might occur in the forward junction characteristics. You are just measuring the two terminal points. If we are conducting a research program, I think you have to get the entire IV curve to make any analysis which is meaningful in this instance.

SMITS

I don't think there is any real contradiction. There is no question that flight experiments should concentrate on short circuit current. The rest of the characteristic is uniquely determined by it.

AUDIENCE (Mr. Lamorte, RCA)

You can take an IV curve with a given current and voltage. Depending on the forward current mechanism, the maximum power point is different in the forward direction, whether you are comparing an ideal diffusion current, a space charge recombination current depending on the factor "a" in

the exponent and/or if it is excess current. These things can vary by almost 100% at the maximum power point.

SMITS

This is perfectly correct. I am saying that the short circuit current is a unique function of the radiation induced defects. So is the IV characteristic. The IV characteristic is a unique function of the short circuit current. It is not a linear function.

MANDELKORN

In regard to the short circuit current and the rate of degradation, I will agree that you can monitor an individual cell and the degradation of the short circuit current is truly an indication of what is happening in that cell. Our problem has been somewhat different. We want to compare two cells in terms of their radiation resistance. We don't want to compare the designs of these two cells because the designs are never finalized. These are experimental cells, you can make them better if you have not optimized your process. Therefore, I feel that for our particular usage and for the people who have been reporting on the comparison of the different cells in terms of radiation damage, they should have been measuring only the diffusion length degradation because we can change the design of any particular cell once we know what we want in the way of a material. We can then work on the process design further so our problem has been different. The one thing that bothers me with short circuit measurements is how do you get around the fact that if you are comparing cells with different coatings, the coatings may have different responses in different regions of the spectrum. I just can't see comparing short circuit currents in order to obtain basic information about diffusion length degradation.

AUDIENCE (Mr. J. Peden, General Electric Company)

I know that some of the experiments that have been done in the past by illuminating the cell during irradiation and they were at a 45° angle to the light source. I wonder if any work has been done to look at the effect of cell degradation as a function of the angle of the cell to the light source.

SMITS

I think that the angular dependence of the isotropic nature of the radiation need only be taken into account in the interpretation of the data. As long as the proton penetrates well through the diffusion length it does not really matter because the defect density per unit volume is what really counts.